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PROMOTION OF YOUNG SCIENTISTS IN LCA

Regional assessment of local emissions of electric vehicles using traffic simulations for a use case in Germany

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Abstract
Purpose In order to assess the global and local environmental impacts of different penetration rates of electric vehicles (EVs) within a region, we developed a life cycle approach based on a detailed traffic simulation assessing local emissions for individual roads with a high time resolution. The aim was to estimate the reduction potential of local emissions such as particulate matter within a region through a substitution of conventional with electric vehicles.
Materials and methods The chosen approach assessing local emissions includes a detailed traffic simulation of a vehicle fleet composed of individual vehicles with a daily schedule. The driving pattern is modeled based on a survey of driving patterns in Germany. Incorporation of traffic density for each road and emissions of electric and conventional vehicles permits conclusions on the reduction potential for each street. Moreover, a feasible reduction potential for a particular region can be assessed. A case study for Aachen, Germany is presented within this paper. For the classification of the local emissions with the usual life cycle assessment approach, a comparison of EV, PHEV, and conventional vehicles has been conducted for Germany providing the results for impact categories according to CML 2001.
Results and discussion Based on simulation results, an estimation of the reduction potential for Aachen for different penetration rates of electric vehicles including particulate matter (PM_{10}), carbon monoxide (CO), and nitrogen oxygen (NOx) is carried out. Electric vehicles possess the highest reduction potential for CO and NOx. Assuming 50 % of the total vehicle fleet in 2010 substituted by electric vehicles, local emissions of CO reduce by 46.6 %, for NOx by 38.8 %, and for PM_{10} by 22.4 %. Due to fluctuations in driving patterns throughout a day, the results are highly time dependent. However, improvements in combustion engine technologies results in an increased reduction potential for conventional vehicles. The direct comparison between the vehicle types showed that the benefit of electric vehicles depends on the considered impact category.
Conclusions Electric vehicles are able to reduce local emissions within a region. Moreover, this approach focusing on the use phase of vehicles within a regional assessment and the resulting local emissions as well as the detailed analysis of the driving behavior allows a distinguished assessment of the reduction potential of electric vehicles. Additionally, an assessment of policy measures such as drive restrictions for conventional vehicles can be simulated on the base of this approach.

Keywords Electric vehicles · Driving behavior · LCIA · Local emissions · Particulate matter · Regional assessment · Simulation · Traffic

1 Introduction

Increasing fuel prices and improved battery technologies promote the mass market introduction of electric vehicles. The main arguments for this introduction are ecologically motivated and can be divided into two aspects. The first aspect deals with the reduction of global emissions emitted by the traffic sector, and the second deals with the impact on local emissions. Assessing both aspects comparing the assets and drawbacks of electric vehicles, various studies carry out a comparative life cycle assessment (LCA) using different approaches (Matsuhashi et al. 2000; McClees and LaPuma 2002; Boureima et al. 2009; Helms et al. 2010; Hawkins et al. 2010). The presented approaches analyzed

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electric vehicles (EVs) regarding their global and local emissions during the life cycle in detail, using simplified approaches for driving pattern. The focus mainly lies on production and recycling of EVs or, especially, attention is paid towards different battery technologies or the ecological impact of different charging systems. An associated research topic deals with the reduction of emissions using a regions or a city's point of view to keep legal limits (Hertle et al. 2006). EVs are a promising technology to reduce global emissions and also local emissions, especially in certain hot spots with high ecological problems.

The assessment of local emissions on a region requires a different approach to model electric vehicles compared to existing analyses. The main difference relates to the scope focusing only on emissions during the use phase. Emissions generated during the rest of the life cycle have to be presented allowing an overview about all impact categories and are included for Germany in this paper. The approach for the regional assessment is done where possible in accordance with the LCA proceeding according the ISO 14040 standard detailed described in the following Section 2. To answer the questions of the reduction potential of electric vehicles with respect to local emissions, the traffic has to be simulated in detailed with the aim to assess the potential for every road throughout the entire day with a timely high granularity. The aims of this work were to present the developed model and to show results regarding reduced local emissions on individual streets. The methodology has been being developed as a part of a research project founded by the German Ministry of Transportation, Building and Urban affairs. As a case study, the city of Aachen in Germany has been chosen. The advantage of this detailed simulation of the driving behavior of individual vehicles can be used for various application fields. For instance, the high time resolution allows the assessment of ecological impact during rush hours which are significantly higher than medium values throughout a day. Moreover, political measures concerning restrictions in the traffic sector can be modeled and assessed to determine the usefulness of different measures.

To be able to interpret the results of the regional assessment of the influence of electric vehicles, the results of an LCA comparing electric vehicles with conventional vehicles will be presented in the beginning of the paper. Afterwards, the regional approach will be described in detail with the aim to stress the discussion why electric vehicles are ecologically worthwhile.

2 Materials and methods

2.1 Comparison of electric vehicles and conventional vehicles for Germany

The LCA studies mentioned in the introduction compare electric vehicles with vehicles with a conventional combustion engine. We use inventory data from different studies to adapt their results to Germany.

2.1.1 Scope and functional unit

The scope of this part of the analysis is the life cycle assessment of different types of electric and conventional vehicles. We differentiate between three types of engines:

- Internal combustion engine (ICE), gasoline
- Electric motor→electric vehicle
- Electric motor and internal combustion engine→plug-in hybrid electric vehicle (PHEV)

For these different types, the following phases of the life cycle are considered: fuel and material supply, production, use phase, and end of life. The vehicle category is a compact car, Golf VI with 898 kg chassis, designed as an EV, a PHEV, or a vehicle with gasoline which are analyzed mainly according to chassis, drive, and Li-ion battery based on Althaus and Gauch (2010), Gaines and Cuenca (2010), and Habermacher (2011). The functional unit is the lifetime of a passenger car with an overall driving distance of 150,000 km within 10–15 years with the assumption that only one battery is required for the whole lifetime. Due to the possibility of a battery replacement during the vehicle lifetime because capacity losses, a variation will be assessed using two batteries. The weight of the battery systems is around 300 kg for an EV for a driving range of 200 km and 100 kg for a PHEV with a reduced driving range.

2.1.2 LCA model details

The LCA model is a synthesis of the mentioned studies and the used values are summarized in Table 1. The chassis and ICE date is taken from Althaus and Gauch (2010), while the data for the electric drive are based on Habermacher (2011) using electric motor from Brusa (74.54 kg). The data for battery cells (lithium–manganese oxide/graphite) with an energy density of 114 Wh/kg is taken from the ecoinvent 2.2 database. The other battery parts are taken from Gaines and Cuenca (2010). The production data for the chassis and the engines are taken again from Habermacher (2011).

For the use phase of the conventional car, the data set from “passenger car, petrol” from the commercial database of the LCA software Umberto 5 is used with a consumption of 7.5 l/100 km (0.053636 kg/l) gasoline The consumption of the EV with an efficiency of 80 % including the charging process and taking into account all auxiliary consumers amounts to 17.15 kWh/100 km (Althaus and Gauch 2010) assuming a 50 % urban usage of the car. The charging energy for the EV and the PHEV is the German power plant mix from Ecoinvent 2.2 database. We assumed that a PHEV drives 80 % of its overall driving distance in the electric

Table 1 Materialization of the product system (n/a = not applicable)

	Unit	Cassis (Golf VI) (Althaus 2010)	ICE drive (Golf VI) (Althaus 2010)	Electro drive (Brusa) (Habermacher 2011)	Battery (Li-ion) (Gaines, Cuenca 2010)
Steel	kg	606.00	135.00	35.17	n/a
Aluminum	kg	3.50	57.00	22.67	30.00
Electrical devices	kg	10	2	n/a	n/a
Plate glass	kg	35	n/a	n/a	n/a
Vulcanized rubber	kg	48.00	3.50	n/a	n/a
Glass reinforced rubber	kg	100.00	n/a	4.45	n/a
Copper	kg	8.00	15.00	10.55	n/a
Lubricating oil	kg	10.50	64.00	n/a	n/a
Card web	kg	18	n/a	n/a	n/a
Lacquer	kg	5	n/a	n/a	n/a
Diode	kg	2	n/a	n/a	n/a
Brass	kg	n/a	n/a	0.97	n/a
Tile	kg	n/a	n/a	0.36	9
Ferrite	kg	n/a	n/a	1.57	n/a
Neodymium	kg	n/a	n/a	1.80	n/a
Polypropylene granulate	kg	40	n/a	n/a	n/a
Polyphenylene sulfite	kg	n/a	30	n/a	n/a
Polyethylene HDPE	kg	12	15	n/a	n/a
Li-ion cell	kg	n/a	v	n/a	261
Total	kg	898	321.5	77.54	300

mode. Eighty-five percent of the total mass of every vehicle not correlated according the material type is recycled due to the recycling quote of the European legislative in EU-Directive 2000/53/EC (2000). The consumption values of the vehicles are determined by using the New European Driving Cycle.

2.2 Approach for a regional assessment of the reduction potential of electric vehicles in a region

Deviating from the approach in Section 2.1, we are changing the scope of the assessment to be able to focus on the regional influence of electric vehicles to stress the ecological effect on the civic population.

2.2.1 Scope and functional unit

The scope of this analysis is the use phase of vehicles within a certain region during a day focusing on the influence of the used drive in the vehicle. Therefore, only the vehicles and their emissions are modeled and the system boundaries are the assessed regions and the compared type of vehicles, in our case passenger cars. The aim of this approach was to be able to stress the advantages or disadvantages of the drive technology for the local population. Only emissions incurred in the examined region are taken into account. This means that only tank-to-wheels values for the emissions for conventional vehicles and only local emissions of electric vehicles are modeled. This approach contains the risk to distort the conclusion of the ecological assessment and hence have to be used only in connection with the LCA approach as described in Section 2.1.

The basis for this approach is a detailed modeling of the driving behavior to assess the location of the emissions of the vehicles. The analysis is accomplished for 2010 for the city region of Aachen in Germany. More details are described later in the case study. The allocation of the emissions to every street in the regions is carried out on a per kilometer basis using the information of the type of vehicle for the amount of emission, the degree of utilization of the streets, and a high time resolution of 15 min.

2.2.2 Modeling of the driving behavior

Realistic driving behavior of private customers The low number of already existing electric vehicles in Germany (KBA (Kraftfahrt-Bundesamt) 2011) inhibits a conclusion on a possible change in driving behavior due to technical restrictions and disparity of electric vehicles such as a reduced driving distance or shortfall of the trip to refuel the vehicle at a filling station. Therefore, we assumed similar consumer habits including today's driving pattern of private

drivers with conventional cars. In other words, technical limitations such as a limited range do not influence the driving patterns of EV users. A detailed description of driving patterns in Germany is available in the study "Mobilität in Deutschland 2008" (MID) based on a survey of 50,000 households describing their own mobility behavior (MID 2010). Within this study, 19,388 driving profiles of vehicles are available describing each trip within 1 day in a year including the driving distance, the purpose of the trip such as leisure or work, and departure and arrival time. Based on a stochastic approach, driving patterns are simulated taking into account the survey described with the aim to evaluate the ecological impact on street level within a town. Based on the MID 2008 study, the average driving distance results in 37.5 km per day and 3.6 trips with approx. 12.2 km distance. The average duration of each stay is 4 h and 20 min (MID 2010).

An accurate description of the traffic flow within a region was the aim of this simulation of German driving pattern in order to evaluate the ecological impacts. A high number of different traffic simulation models exist differentiating two levels of detail (König 1996). On the one hand, macroscopic models simulate a high number of vehicles in groups using vehicle density and average speed with the result of short calculating times and the ability to simulate traffic jams. On the other hand, microscopic models describe the pattern of an individual vehicle and can be utilized to assess crossroads or short freeways resulting in long computing times. A mixture of both models is a mesoscopic model combining the advantages of both for a realistic simulation of smaller areas with detailed information of each vehicle such as the exact driving distance. Our approach includes the implementation of driving patterns described in Helmschrott et al. (2010) using a mesoscopic model based on the information of the MID study.

This simulation model consists of three parts which are required to simulate the traffic flow in a region: geographical location of residential areas and road maps, generation of a vehicle fleet with driving data and home location, and the simulation of the driving pattern of this fleet within the region studied. The first part makes up the basis for the simulation generating of road maps and classifying regions in residential or industrial areas. Depending on the size and location of the area under consideration, a roadmap based on disposable geographical data is build automatically. Afterwards, areas on the roadmap are classified into residential and industrial areas to allocate vehicles to their homes and destinations, respectively. The second part, the generation of the vehicle fleet, adapts the driving patterns provided by the MID study to create a vehicle fleet according to the driving groups described in Table 2. The fleet size matches the amount of vehicles of the region. Each vehicle gets an individual stochastic driving profile with a certain number of trips, distances, and destinations with a certain purpose such as work or leisure according to his driving group. Afterwards, the fleet is assigned to residential areas within the region and each vehicle receives a home location. From this starting point, the geographic locations of the following destinations are determined depending on the purpose and distance. For example, if the next destination has the purpose "work" and the distance of 10 km, the algorithm is searching for an industrial area and this distance and allocates the destination for the next trip there. This step is repeated until the vehicle reaches its home destination. As a result, each vehicle in this fleet has an individual driving schedule with times and destinations. The third and last step combines the information about geographic locations of the streets with the driving plans of the vehicle fleet with the help of a traffic flow simulation tool called Multi-Agent Transport Simulation Toolkit (MATSim) (2011). This tool uses these information and simulates the vehicles movement along the streets from their starting point to their destinations under consideration of speed limits and the capacity utilization of the streets.

Table 2 Classification of driving types, characterization and percentage of population

Driving type	Percentage of population	Possible number of trips per day	Maximum driving distance
Private	57.05 %	0, 1, 2, 3, 4	20, 40, 60, 150
Commuter—short	28.63 %	0, 2, 3, 4	20, 40, 60
Commuter—long	14.32 %	0, 2, 3, 4	60, 100, 150

The result of these three steps is a detailed description of the driving pattern of the vehicle fleet within a region with detailed whereabouts of each vehicle, roads utilized, arriving and departure times, destinations, and home locations. This enables us to differentiate between different vehicle types according their driving distances or home areas.

To be able to assess the impact of the fleet ecologically, each vehicle needs additional information with respect to the vehicle type such as the vehicle class and the type of the engine. Nowadays, nearly all private vehicles have an internal combustion engine and around 71.9 % of them are powered with gasoline. The most of the other 28.1 % are fueled with diesel (KBA 2011). Based on the fact that vehicles fueled with diesel normally drive longer distances and have a higher annual driving distance compared to vehicles fueled with gasoline, we assume that electric vehicles will mainly substitute vehicles powered by gasoline, and PHEV will substitute vehicles fueled with diesel. Therefore, the distribution between EVs and PHEVs corresponds to the distribution between vehicles fueled with gasoline and diesel.

In combination with the MID (2010) study providing very detailed information about the existing vehicle fleet in Germany concerning the size of vehicles used, differentiation into several vehicle groups is possible. Table 3 shows six groups with their respective proportion in the fleet and their diverse consumptions. The driving distance for EVs is around 150 km to cover most distances within a day in a region. PHEVs have an electric range of 40 km and drive afterwards with their ICE fueled with gasoline. Due to the different consumptions of the vehicle types, each group requires different battery sizes to reach the expected range.

After the detailed description of the vehicle types, an allocation between the existing fleet with driving profiles and the vehicle types is required to complete the modeling process. The starting point is a vehicle fleet in 2010 without EVs or PHEVs with the result that the entire fleet consists of vehicles with ICE. To simulate an increase of EVs and PHEVs according to the proportion of the vehicle types, EVs and PHEVs are allocated randomly to a driving type according to Table 1 depending on the investigated penetration rate such as 20 or 50 % penetration. For instance, a long-distance commuter has a higher likelihood to be allocated to a PHEV than to an EV because of the restricted driving distance of an EV, and a private driving type is in most cases allocated to an EV because of the short trip distances of private drivers. Afterwards, each allocation has to be verified according to technical restrictions and the randomly chosen driving distances.

In order to improve allocation of EV to certain areas, it is possible to utilize socioeconomic data as the brand of vehicles; the vehicle age or buying power can be used to estimate areas with a higher penetration rate of EVs even if the average penetration rate is still very low. However, this requires a detailed analysis of buying behavior of vehicle drivers and is not the object of investigation in this paper.

Inventory assessment Our ecological assessment is a first approach for the assessment of the emission of electric vehicles on a city region with the consequence that only parts of the life cycle inventory analysis are carried out. However, to estimate the significance of the results, we started to evaluate some main local emission categories regarding the traffic sector: nitrogen oxide (NOx), particulate matter (PM_{10}), and carbon monoxide (CO). These emission categories are analyzed on a street level. However, the analysis carried out can only assess the reduction potential of newly generated emissions by the traffic. Background contamination such as the emissions of power plants and the exposure time of the emissions are not accounted for. This simplification is necessary because the fair according to the input involved for the used electric energy to a certain power plant is not possible.

Unfortunately, other categories like noise emissions benefiting from the integration of EVs providing a high reduction potential could not be implemented because of the complexity of this evaluation which forbids an easy integration in the model due to the different influencing factors such as road surface. Depending on engine type, used fuel, and vehicle type, the amount of local emissions vary significantly. Therefore, each type is examined separately. The boundary values for NOx, PM_{10}, and CO emissions for vehicles with combustion engines are shown in Table 4, divided according to the European emission standards (EURO 1-4 (1998), EURO 5, 6(2007)). For some values without defined European emission standards, reasonable assumptions based on average values for vehicles in these groups according to the KBA (2011) have been defined. Moreover, 43 % of the vehicles with combustion engines comply with EURO 4 standard, and only 7 % already comply with the highest level today, EURO 5. In 2015, all newly produced vehicles have to satisfy EURO 6 standard. Based on information about the age of today's vehicle fleet, the proportion of vehicles in each group can be calculated. In order to assess a realistic reduction potential, electric vehicles have to be integrated in a future vehicle fleet with a changed proportion. For the results in this paper, we use in our simulations the vehicle fleet in 2010.

Due to the fact that electric motors do not emit any NOx, PM_{10}, or CO emissions during the driving process, these

Table 3 Differentiation of the used vehicle types and associated consumption rates for the regional assessment

Vehicle type	Percentage of population	Consumption			
		ICE	EV	PHEV	
		l/100 km	kWh/100 km	kWh/100 km electric	l/100 km conventional
Subcompact car	12 %	4.4	14.0	15.7	4.2
Compact car	18 %	5.2	15.6	17.5	4.7
Medium-sized class	19 %	5.9	19.5	21.8	5.9
Upper medium-sized class/upper class	26 %	7.1	22.5	25.2	6.8
Roadster/sport utility vehicle (SUV)	13 %	8.5	22.2	24.9	6.7
Vans	12 %	6.7	28.6	32.0	8.6

Table 4 Norm data for vehicles with ICE for PM_{10}, CO, and NOx in grams per kilometer and own assumptions for the calculations

ICE Fuel type		Emission categories			
		PM_{10}		CO	NOx
		Motor emissions	Overall		
Diesel	Euro 1	0.180	0.2126	3.16	*(0.60)*
	Euro 2	0.080	0.1126	1.00	*(0.60)*
	Euro 3	0.050	0.0826	0.64	0.50
	Euro 4	0.025	0.0576	0.50	0.25
	Euro 5	0.005	0.0376	0.50	0.18
	Euro 6	0.005	0.0376	0.50	0.08
Gasoline	Euro 1	*(0.012)*	0.0446	3.16	*(0.25)*
	Euro 2	*(0.012)*	0.0446	2.2	*(0.25)*
	Euro 3	*(0.012)*	0.0446	2.3	0.15
	Euro 4	*(0.012)*	0.0446	1	0.08
	Euro 5	0.005	0.0376	1	0.06
	Euro 6	0.005	0.0376	1	0.06

Own assumptions for the calculations were set in italics

values from motor emissions can be set to 0. However, as shown in CORINAIR (2005), each vehicle produces PM_{10} emissions because of the road abrasion. Consequently, the PM_{10} emissions are composed of motor emissions and driving emissions divided up into abrasion of tire wear and break wear which amount to 0.0326 g/km for EVs (Miguel et al. 1999). Compared to engine emissions of vehicles fueled with gasoline, road abrasion emissions are the dominating factor, and the reduction potential for electric vehicles is very low if the road abrasion for both vehicles is similar. However, EVs and PHEVs will have a reduced amount of brake wear emissions due to the recuperation with a possible saving of 8.8 mg/km (Warner et al. 2002) which is not proven yet with accurate measurement methods. Therefore, we use the same road emissions for every motor type. To summarize, even EVs have PM_{10} emissions during the driving process and for vehicles with ICE, the motor and road abrasion emissions have to be added. PHEVs behave, while driving with the electric motor, like an EV and change their behavior afterwards to the same values as vehicles fueled with gasoline.

Case study: electric vehicles in Aachen, Germany The adaptability of the modeling highly depends on the investigated region and available information. Therefore, we chose the city region of Aachen, Germany, as an example due to a high availability of local data such as traffic density or socioeconomic data that can be used to improve the model to generate realistic conclusions.

The city region of Aachen has a population of 566,347 inhabitants (31 December 2009) with 290,868 automobiles of which 86.27 % are passenger cars which are modeled (IT NRW 2011). Due to the lack of driving behavior of light duty vehicles and other automobiles, these types are not represented. The geographic location of the city region of Aachen within Germany is shown in Fig. 1, highlighting the traffic density in the city center of Aachen. The information about traffic density in the region was provided by the Stadt Aachen in a report about the field mapping of noise in the year 2008. The description of the traffic density in Aachen allows us to improve the driving behavior in our model for the region.

3 Results

The results for both approaches for the assessment of electric vehicles are presented and interpreted in this chapter.

3.1 Impact assessment for the comparison of electric vehicles and conventional vehicles for Germany

The impact assessment results for the general approach are presented in Table 5 using the impact categories according

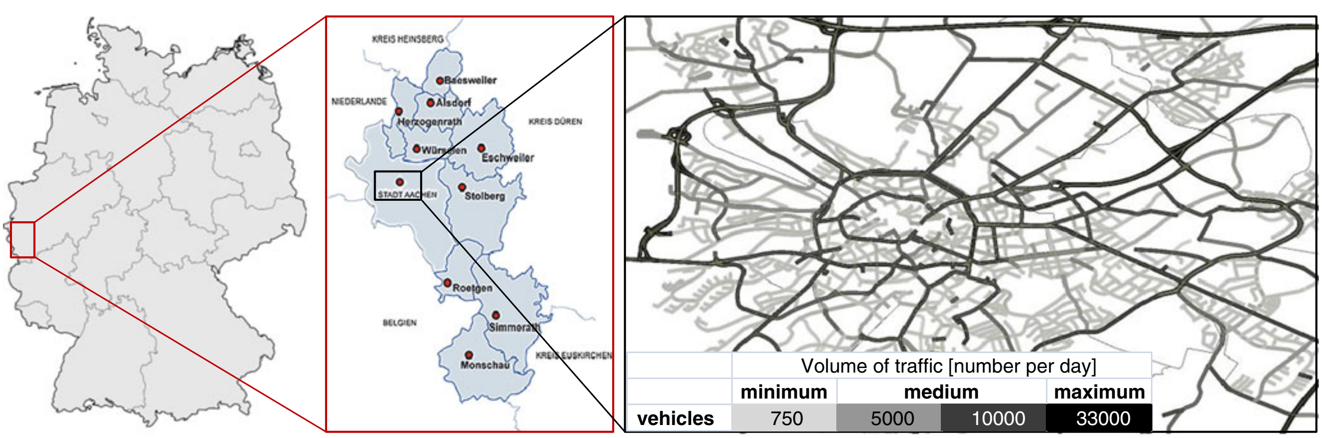

Fig. 1 City region of Aachen (*middle*) and its location within Germany (*left*) and traffic density in the city center of Aachen for 1 day (*right*)

Table 5 Impact assessment (CML 2001) for EV, PHEV, and ICE vehicles per vehicle life cycle (bold highlighted: lowest value for the impact category)

Impact category	Unit	EV	PHEV	ICE
Marine aquatic ecotoxicity				
MAETP 100a	kg 1,4-DCB	1,095E+05	1,118E+05	**7,128E+04**
Freshwater aquatic ecotoxicity				
FAETP 100a	kg 1,4-DCB	3,198E+04	3,271E+04	**2,058E+04**
Terrestrial ecotoxicity				
TAETP 100a	kg 1,4-DCB	5,924E+00	6,185E+00	**5,339E+00**
Odor				
Odor	m3 air	1,738E+08	1,636E+08	**9,810E+07**
Human toxicity				
HTP 100a	kg 1,4-DCB	**7,904E+03**	1,106E+04	1,110E+04
HTP unlimited	kg 1,4-DCB	2,580E+04	2,859E+04	**2,095E+04**
Impact of ionizing radiation				
Impact of ionizing radiation	DALYs	2,168E-04	1,877E-04	**5,936E-05**
Global warming potential				
GWP 100a	kg CO2-Eq	**2,451E+04**	2,774E+04	3,841E+04
Land use				
Land use	m2a	8,710E+02	8,350E+02	**6,034E+02**
Photo-oxidant formation (summer smog)				
Low-NOx POPC	kg ethylene	**1,889E+00**	3,429E+00	8,518E+00
High-NOx POPC	kg ethylene	**3,414E+00**	4,820E+00	9,209E+00
EBIR	kg formed	**2,454E+00**	3,816E+00	8,134E+00
MIR	kg formed	**1,290E+00**	2,312E+00	5,708E+00
MOIR	kg formed	**2,001E+00**	3,332E+00	7,673E+00
Resources				
Depletion of abiotic resources	kg antimony	**1,782E+02**	1,974E+02	2,517E+02
Marine sediment ecotoxicity				
MSETP 100a	kg 1,4-DCB	1,229E+05	1,280E+05	**8,628E+04**
Freshwater sediment ecotoxicity				
FSETP 100a	kg 1,4-DCB	7,084E+04	7,326E+04	**4,780E+04**
Stratospheric ozone depletion				
ODP balance	kg CFC-11-	**1,313E-03**	2,116E-03	4,942E-03
Acidification				
European average	kg SO2-Eq	**6,206E+01**	7,095E+01	9,318E+01
Generic	kg SO2-Eq	**6,212E+01**	7,062E+01	9,141E+01
Eutrophication				
European average	kg NOx-Eq	**4,065E+01**	4,701E+01	6,389E+01
Generic	kg PO4-Eq	1,112E+02	1,009E+02	**4,165E+01**

to CML 2001. Depending on the chosen impact category, EV and PHEV can be ecological beneficial or not compared to conventional vehicles. On the one hand, the global warming potential (GWP) is lower for electric vehicles than for vehicles with an ICE. On the other hand, the eutrophication is highest for EV.

A more detailed analysis is shown in Fig. 2, dividing exemplarily the global warming potential for the three vehicle types in the different phases of their life cycle. The use phase has the highest share of emissions for each vehicle type. It especially dominates with around 83 % of the GWP of a vehicle with an ICE. The lower the emissions are during the use phase of the vehicle, the less important is the use phase for the total GWP while the importance of the other phases rises. This has to be considered for the ecological assessment of electric vehicles in countries with a very low GWP of the energy mix such as Norway. Even with very low emissions during the use phase, EV can never be CO_2e free in their LCA.

The uncertain battery lifetime caused by the insufficient usage experience in the long term is still an uncertain variable for the life cycle assessment. Therefore, the assumption

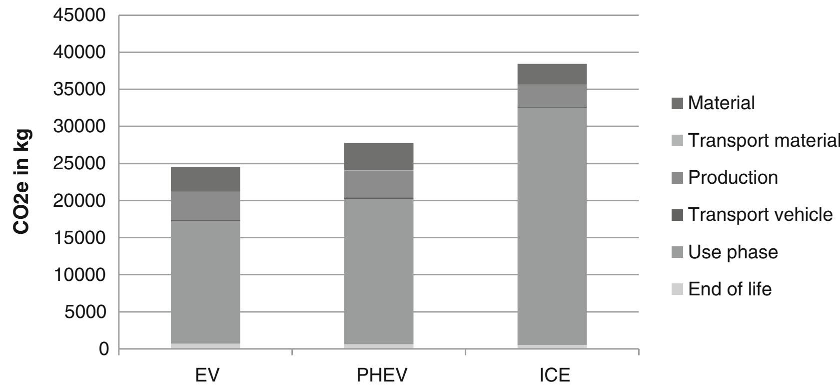

Fig. 2 Global warming potential (CO_2e emissions) of vehicles with different drives: EV, PHEV and ICE using CML 2001 in kilograms CO_2 equivalent per vehicle life cycle

of only one battery during a lifetime is changed by assuming that the battery has to be replaced. The results are only presented for the EV because the battery size of the EV is larger than the battery of the PHEV resulting in a higher ecological effect. The additional battery causes an increase of 5.2 % of the photo-oxidant formation (high-NOx POPC), of 3.3 % of acidification (European average), of 3.7 % of human toxicity (HTP 100a), of 3.0 % of global warming potential (GWP 100a), and of 1.6 % of eutrophication (European average). The increase in the other impact categories according to CML 2001 is lower than 3.0 %. Hence, the increase in the values of the impact assessment of an EV is only slightly and does not change the overall result presented before. The impact on the results of the PHEV is correspondingly even more insignificant and no longer assessed in the following part.

3.2 Local emissions due to a high penetration of electric vehicles within a region

The results for the different vehicle types show that depending on the impact category, EV are not always beneficial for the environment. Therefore, this second, regional analysis stresses influence of EV on local emissions which affect the life quality in urban areas.

The developed model provides results for different emissions based on realistic driving behavior in Germany with a time resolution of a year for global emissions and 15 min for local emissions. These results can be aggregated for a region or be provided for each street. The results are exemplary for the model.

3.2.1 Daily amount of traffic

Based on the driving behavior in combination with the statistical information of the city region of Aachen and the traffic densities in this region, the amount of vehicles during a day for each road can be calculated. The results for five exemplary roads in the region are shown in Fig. 3. The traffic on the main roads is higher than on side roads as expected and indicates a higher impact of commuters during the morning and in the early evening. The resulting effect is less for side roads which only handle few vehicles during a day. On the highway, the amount of vehicles is low compared to the traffic density of Aachen because of missing transfer traffic in the simulation. Therefore, highways are

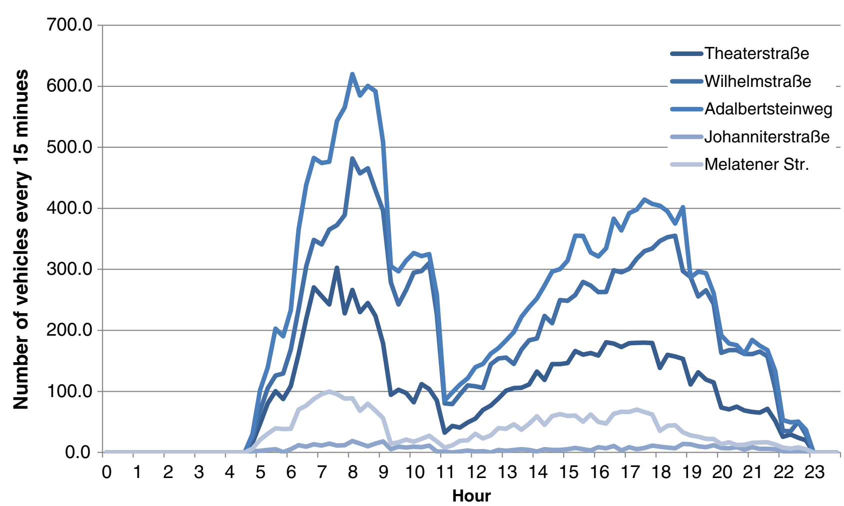

Fig. 3 Daily traffic on five different roads in the city center of Aachen for 24 h in 15-min resolution: main roads: Wilhelmsstraße, Wilhelmstraße, Theaterstraße; side roads: Johanniterstraße, Melatenerstraße

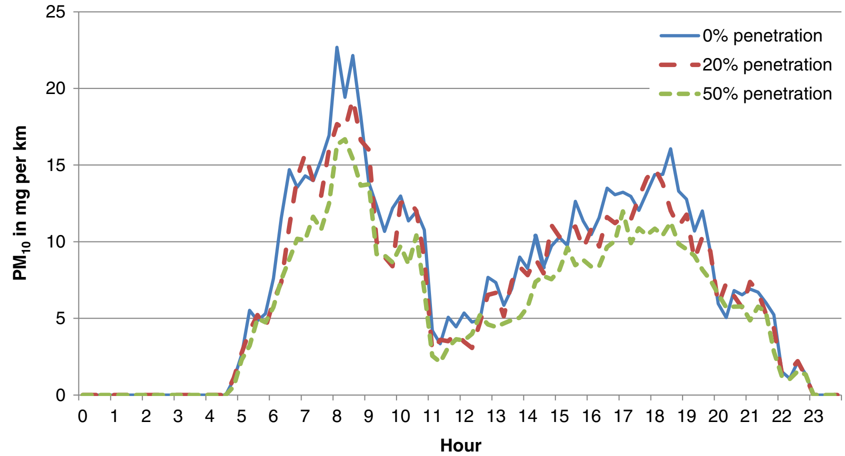

Fig. 4 PM_{10} emissions for 24 h in 15-min resolution for three different penetration rates of EVs in the Wilhelmsstraße, Aachen

not investigated any further within this paper. According to the MID study, two peaks during the day as a consequence of the commuters can be observed. The private traffic is spread throughout the day. The randomness of the routes and destinations chosen leads to variations in the daily traffic of some 50–100 vehicles per time step. Hence, the simulation has to be repeated several times to reduce the stochastic influence. The following results are average values.

For a main road in the city center in Aachen, Wilhelmsstraße, the impact on local emissions will be shown in the following. Due to equally distributed electric vehicles in the region, the course of the results is quite similar for the other roads only with variations in the total amount of emissions.

3.2.2 Particulate matter—PM_{10}

The reduction potential of different penetration rates of EVs on particulate matter is shown Fig. 4. The course of the emissions throughout the day fluctuates according to the driving pattern reducing the emissions obviously. Thus, the influence due to 50 % of electric vehicles on the PM_{10} is around 23 % in the average during the day compared with a vehicle fleet in 2010. Nevertheless, the influence of remaining emissions in the air cannot be presented with the result of showing only the reduction of produced particulate matter. However, a reduced production will lower the overall radiation in the long term. With a vehicle fleet of vehicles in 2030, the influence of EVs will be significantly lower due to the reduced emissions of ICE in a future vehicle fleet.

3.2.3 Nitrogen oxygen and carbon monoxide

The results for NOx and CO take a similar course, therefore only the course of the NOx emissions is shown in Fig. 5 for a 20 and 50 % penetration. The course of these emissions is depending on the driving patterns as before. Clearly, the reduction potential is higher due the EVs than for PM_{10} because the ICE emissions are dominating the generation. On the contrary, an electric motor emits none of these emissions. In conclusion, a 50 % penetration with electric vehicles reduces NOx emissions about 38.8 % and CO emissions about 46.4 %.

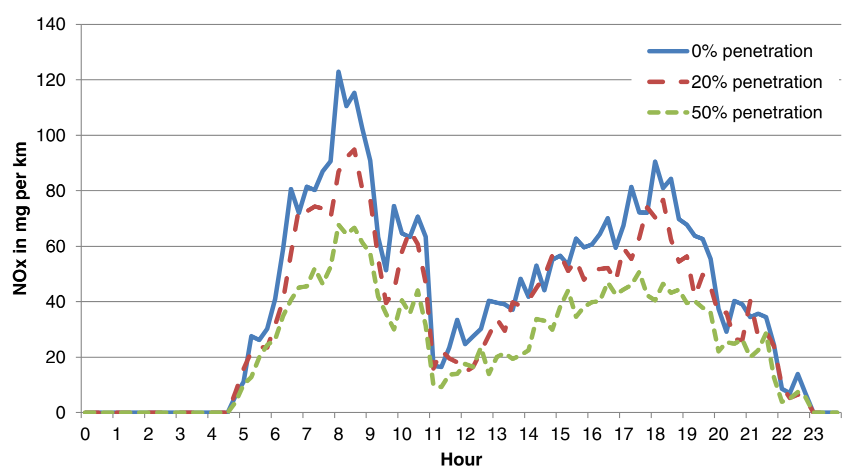

Fig. 5 NOx emissions for 24 h in 15-min resolution for three different penetration rates of EVs in the Wilhelmsstraße, Aachen

4 Discussion

The results of both conducted analysis show that the question if EVs are beneficial for the environment is not answered easily because, depending on the scope of the analysis and the analyzed emissions, the result can be ambiguous. However, EV posses the potential to reduce global and local emissions such as particulate matter. This can be important for certain regions at the border of their prescriptive limits for particulate matter within a day or year.

This paper had examined the ecological impact of EVs within a region and compared different types of vehicles for their life cycle. For the local assessment, a mesoscopic model is used including various information of the region to simulate a realistic driving behavior. This investigation has revealed that the reduction potential of PM_{10} is existent but highly depends on the vehicle fleet taken for comparison with the result that the impact of EVs concerning PM_{10} is minor, especially in the years around 2030. However, the impact on the CO and NOx emissions is significant higher and could improve the situation in the city centers. Though, the validity of the results of the model is dependent on the assumptions used and input data bordering the application area.

The comparison between the different vehicle types has not shown a distinct result because depending on the impact category, EV or conventional vehicles have the higher impact. Especially, the result for the global warming potential is highly depending on the used energy mix leading to alternating results for different countries. However, a higher share of renewables in the energy mix will tip the scales for electric vehicles by reducing their emissions during the use phase significantly. Nevertheless, the energy produced for EV leads also to a rise of local emissions produced by power plants near urban areas and has to be accounted in the local assessment. In our case, the next coal power plant is around 20 km western from the city center of Aachen and has not been taken into account.

5 Conclusions

The assessment approach of the local impact of electric vehicles for a region presented differs from the conventional approach used for electric vehicles. The results of both approaches are presented in this paper with their different interpretations. The main differences concern the system borders of the studies and the detailed description of the driving patterns which are used to implement this model to simulate the routes of nearly every vehicle in a region with the aim to assess the resulting local emissions on every street influencing the life quality in a region. Both approaches contribute to the question if electric vehicles are environmental friendly even though the focus and the statement might differ.

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